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Workshop Report on Modern Millimeter Wave Systems

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WORKSHOP REPORT ON

MODERN MILLIMETER WAVE SYSTEMS

by

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I. INTRODUCTION

Because of the advantage in size and bandwidth, millimeter radar systems have many civilian, as well as military, applications. Use of low profile planar structures in devising waveguiding and radiating elements in a single substrate certainly will enhance their desirability. With recent advances in electronic circuit and device fabrication in integrated circuit technology, a partial, or even a total, integration of passive and active elements into complete millimeter wave systems becomes a realistic goal to pursue. A 2-day workshop under the sponsorship of the U.S. Army Research Office, Research Triangle Park, North Carolina, on Modern Millimeter Wave Systems was held in Estes Park, Colorado, October 22-24, 1980. Objective of the workshop was to assess the state-of-the-art in millimeter waves, and to discuss the directions for future research and development efforts necessary for the realization of integrated millimeter wave systems.

Sessions included in the workshop, together with their organizers, are listed as follows:

1. Technology Overview (Dr. Timothy T. Fong, TRW)
2. Waveguides and Passive Components (Professor David C. Chang, University of Colorado)
3. Antennas and Radiation (Professor Tatsuo Itoh, University of Texas)
4. Round Table Discussion (Professor Raj Mittra, University of Illinois).

The workshop was administered by Professor S.W. Maley, in cooperation with the Center for Conferences and Management, University of Colorado. The list of attendees is included in the Appendix. In this report, we shall summarize the results and discussions given during the workshop.

II. MILLIMETER-WAVE DEVICES AND SYSTEMS

The objective of this session was to review the state-of-the-art on millimeter-wave technology and to bring the attendees of the workshop up-to-date on the existing and planned millimeter-wave systems. This session was designed to set the stage for the workshop and to derive a set of recommendations for future research and development work in millimeter-wave technology, particularly in the area of millimeter-wave integrated circuits. The size, weight, cost and performance issues, coupled with fundamental considerations in many system configurations, clearly identified the need for integrated circuit approaches for system integration. The key question of establishing a proper technology for future research and development to benefit millimeter-wave systems was the focal point of discussion for the workshop. This session was designed to provide the background information to facilitate such discussions.

Four papers were presented in this session. The first paper, presented by Dr. Harold Jacobs of the U.S. Army ERADCOM, highlighted the Army's thinking on existing and planned millimeter-wave systems, and addressed particularly large volume applications where integrated circuit technology would be essential. The second paper was presented by Dr. T.T. Fong of TRW Systems, which outlined the solid state device technology, particularly power generation devices, and described the state-of-the-art in transmitter technology. The third paper, presented by Dr. F.J. Bernues, Hughes Research Lab, focused on receiver technology and systems constructed today using conventional waveguide approaches. The fourth paper, presented by Dr. J. Wiltse of the Georgia Institute of Technology, provided a broad review of both military and civilian applications of millimeter-wave systems. In addition, Professor Russell Hayes of the Department of Electrical Engineering, University of Colorado, presented in the second session of this workshop a paper reviewing the state-of-the-art material research for millimeter-wave systems. For the sake of continuity, a summary of his discussion is also included in this session.

2.1 Millimeter-Wave Sensor Technology and Applications

Dr. Harold Jacobs outlined the existing Army programs in the millimeter-wave arsenal and made a strong point about the need for integrated circuit approaches to meet the cost objectives. The following points were emphasized:

- Useful millimeter-wave systems are short range sensors because of the atmospheric attenuation; as such, low power systems using self-mixing technology are ideal for millimeter-wave applications.
- A large quantity production is envisioned for the sensor applications, and cost is a high priority issue. To enhance low cost sensors, integrated circuit approaches are essential.
- The speaker strongly favors the dielectric image waveguide integrated circuit approach because of its ruggedness and simplicity in construction. A variety of components and subsystems constructed by dielectric image waveguides was reviewed.

2.2 Millimeter-Wave Solid State Devices

Dr. T.T. Fong reviewed the state-of-the-art on power generation of solid state devices in the millimeter-wave spectrum, such as IMPATT and Gunn devices. Future power projections for these devices were also provided. The overall existing technology base for present device development and the new technology required were also outlined.

- Solid state devices, such as IMPATT and Gunn devices, have come a long way in terms of power generation capability. CW power levels in the several watts' range and peak power of several tens of watts have been demonstrated. These power levels are adequate for many practical radar, sensor and communication applications.

- Current device capability is limited by the material parameters. Sophisticated doping profiles for improved power efficiency in the millimeter-wave spectrum require improved material growth capability, such as MBE.

- Three separate materials have been used for device development: silicon, GaAs, and InP. The frequency and efficiency of each material were reviewed. It was concluded that silicon has the broadest frequency response, but low efficiency. GaAs tends to be limited to below 50 GHz with high efficiency. InP offers high efficiency and lower noise performance between 40 and 100 GHz, and may be a device that will receive considerable development in the future.

- IMPATT diodes are high power with high noise level and are ideal for transmitter applications. By combining these devices in a power combiner, power levels ten times that for a single device can be achieved. For example, 10 W CW at 40 GHz and 60 W peak power at 94 GHz have been achieved. Gunn devices, on the other hand, are low power and low noise, suitable for receiver local oscillator applications.

2.3 Millimeter-Wave Receiver Applications

Dr. F.J. Bernues outlined a wide range of millimeter-wave subsystems constructed with today's technology. Prototype hardwares with a considerable amount of sophistication have been implemented and demonstrated. The speaker felt strongly that the millimeter-wave technology is well in hand to meet the need for most system applications. He also emphasized the value of the conventional metal waveguide approach for system integration. The following points were highlighted:

- The existing technology based on metal waveguide components is sufficient for many system applications. Many subsystem hardwares were reviewed to establish the maturity of the technology.

- The beam lead mixer is an important device development and the subharmonic mixer is an important circuit development for receiver technology.

- Above 140 GHz, quasi-optical techniques become more suitable for receiver developments. Hardwares were reviewed for 217 GHz quasi-optical mixer.

2.4 Present and Future Millimeter-Wave Applications

Dr. Wiltse spoke on a wide range of millimeter-wave applications, both military and civilian. He outlined the possibility of using millimeter waves for radar in automobile collision avoidance and other systems, for medical research, and for instrumentation and measurements. In his travels around the world, he found a strong interest in millimeter waves in Europe and Israel. The following points highlighted some of his talk:

- Radar instrumentation and data collection to enhance modern system design still need a lot more work. Radar cross-section, propagation in rain, clutter and range are still important issues needed to be resolved through better instrumentation and measurements.

- The millimeter-wave applications are not limited to military applications and there is a wide range of civilian applications we should address.

- The U.S. is lagging behind in high power tube development such as E10's and gyrotrons. There is a need to expand such developments in the U.S.

2.5 Material Research for Millimeter-Wave Systems

Dr. Russell Hayes presented a reivew on the state-of-the-art material and device research for millimeter-wave systems in the second session. The review covered several different angles including circuit architecture, material technology and source structure:

- Hybrid vs. monolithic circuit development: Using a GaAs semi-insulating substrate with resistivity $\rho > 10^7\ \Omega$-cm for circuit integration is an attractive concept. It will be important if low-cost sophisticated systems are to be developed.

- Semiconducting materials: Present choices for TED and MESFET devices are mainly restricted to GaAs and InP. Arguments in favor of InP are based principally on central valley electron dynamics. Efficiency values for CW TE oscillators using the two materials were calculated which show InP would go about twice the frequency of GaAs.

- Sources: TED's are low noise devices with InP being superior because of the nature of hot electron diffusion and because some of the random scatterings can be altered at a high-field environment. Other materials, such as GaInAsP, are future possibilities. MESFET's are a source to be considered. The choice between InP and GaAs for FET's has often been based upon the peak electron velocity reached in the two materials.

- GaAs material technology is reasonably matured. Importance of GaInAsP/InP is emerging as a result of the interest in optical communication near 1.1 - 1.3 μm. Acceleration of InP technology will benefit microwave- and millimeter-wave system development.

III. WAVEGUIDES AND PASSIVE COMPONENTS

In this section, emphasis was placed on the assessment of difficulties one usually encounters both in terms of analytical understanding and fabrication/application of millimeter-wave components. Effort was also expended in identifying what would have to be overcome in order to achieve system integration consistent with IC technology. Speakers in the session included Dr. Jörg Raue of TRW, Inc., Professor David Chang and Professor Russell Hayes of the University of Colorado, Professor Tatsuo Itoh of the University of Texas, and Professor Steven Schwarz, University of California-Berkeley. Summaries of their presentations and discussions are given in this chapter. Professor Hayes' presentation was included previously in Chapter II.

3.1 Propagation Characteristics of Printed-Circuit Guides

Propagation characteristics of a wide class of striplines and planar dielectric guided waves derived from printed circuit technology were discussed and compared by Professor Tatsuo Itoh.

- Microstrip structures and various modified forms are usually characterized by not having a low frequency cutoff and reasonably small dimensions. In this class of structures, coplanar guides, the stripline, and the microstrip have higher losses and more limited bandwidths than the inverted microstrip, trapped inverted microstrip, and suspended microstrip structures.

- The dielectric image guide, insulated image guide, inverted strip dielectric guide and groove guides usually have low loss, but are susceptive to radiation loss at bends and other discontinuities. Composite waveguiding structures derived from the simple image guide can support leaky mode(s) instead of surface wave mode(s), depending on the choice of relevant material parameters and dimensions.

- Fin-line and slot-line structures usually are characterized by high loss but broad bandwidth compared with microstrips.

- To establish a figure-of-merit for a given guiding structure, one has to consider problems concerning the transition to a metallic waveguide, compatibility to passive or active devices, isolation to adjacent guiding structures, propagation and radiation losses, and compatibility with radiators. It appears that inverted microstrip and strip slotted lines both possess more desirable features than other planar guiding structures discussed.

3.2 Guided Wave Analysis

Analytical methods needed for the analysis of planar waveguiding structures were reviewed by Professor David Chang. He pointed out the limitation of the available techniques for attacking two-dimensional discontinuity problems that are typically encountered in printed circuit waveguide and antenna practices. Highlights of his presentation are given as follows:

- Waveguiding phenomenon of a given dielectric or microstrip planar structure usually can be explained physically by a trapped surface wave, a trapped space wave, or in the case of a more complex structure, by a combination of both waves.

- Coupling between two parallel open waveguiding structures can be analyzed in most cases by the same technique used for the propagation characteristics of a single guide. The two basic coupling mechanisms, i.e., evanescent-field coupling and mismatch coupling, are well understood at the present time.

• Bending loss of an open waveguiding structure comes from scattering at the junction of two waveguide sections with different curvatures as well as continuous surface-wave radiation along a bend. Methods for studying the latter have been developed for simple structures, and they can sometimes be extended to more complicated, composite structures.

• Two-dimensional junction discontinuity problems remain largely unresolved because of the severe limitation of available analytical tools. In the case of a microstrip, an approximation based upon the assumption of the so-called magnetic wall model yields reasonable junction susceptance, but is not expected to work well at millimeter-wave range when radiation and substrate dispersions become significant. Knowledge of the junction effect is essential in the design of most circuit arrangements.

3.3 Near Millimeter Wave IC

Fabrication of near millimeter-wave integrated antennas, waveguides and detection systems were discussed by Professor Schwarz. A silicon waveguide, etched out from a silicon wafer and supported by a thin silicon membrane, was demonstrated. A tapered silicon waveguide antenna was shown to couple effectively to a bismuth film bolometer with 0.7 dB coupling loss, using a V-shaped metallic coupler deposited onto the silicon membrane.

• A planar Schottky-diode mixer can be integrated with a waveguide/ antenna structure. However, careful mask alignment is required to keep the diode size down to tolerable levels. Small dimensions and carefully chosen doping profiles are essential to assure small RC time constants.

- Integrated receiver systems can be made with the exception of the local oscillator. One problem with LO is likely to be low power because of the small dimensions. Harmonic mixers provide the advantage of noise suppression and reduced LO frequency. The concept of coherent source arrays may circumvent the low power problem.

3.4 Millimeter Ferrite Components

Recent developments in millimeter-wave ferrite devices were reviewed by Dr. Jörg Raue. He pointed out that:

- At frequencies above 50 GHz, the ferrite material limits the progress of component development. Saturation magnitization must be increased to 6000 Gauss and above for satisfactory design of components such as circulators, switches, isolators and phase shifters.

- In search of materials and compound materials, one should be able to tolerate reasonable amounts of RF loss, since in most cases, mismatch and other waveguide-related loss mechanisms are the major factors in determining the total losses.

IV. ANTENNA CONCEPTS AND DESIGNS

In this section, the state-of-the-art of millimeter-wave antennas and arrays design was reviewed. Projection of future direction was also attempted. The major conteders in this frequency range are leaky-wave dielectric antennas and microstrip patch antennas. Advantages and disadvantages of both antenna forms and their compatibility with the current printed circuit technology were discussed. Speakers in this session included Dr. Felix Schwering of the U.S. Army Communications R&D, Professor Raj Mittra of the University of Illinois, Professor A.A. Oliner of the Polytechnic Institute of New York, Dr. Art Sandoris of Harry Diamond Laboratory, Dr. Donald Huebner of Ball Aerospace, and Dr. Oren Kessler of Texas Instruments. Summaries of their presentations are given as follows:

4.1 Millimeter-Wave Antenna Research at Fort Monmouth

Dr. Felix Schwering discussed a number of millimeter-wave antennas being studied by the Army at Fort Monmouth. They include lens antennas, dielectric surface-wave and leaky-wave antennas, dielectric disk antennas, and microstrip patch arrays.

- Spherical lens antennas have been used for a compact millimeter wave transceiver. They typically have 6.8° beam widths.

- Two-dimensional analyses have been applied to estimating the radiation characteristics of surface- and leaky-wave antennas, typically made of silicon. An example of a measured pattern for a surface-wave antenna, with its length $L \approx 8\lambda$, indicated a gain of 16.2 dB.

- Gain and scanning capacity of leaky-wave antennas of the grating type have been studied. Although frequency scanning is readily available, other means of electronic scan are often desirable. Distributed PIN diodes are attached at the side of a silicon waveguide with periodic metal strips. In this matter, the beam can be scanned electronically without changing the operating frequency.

- Two antennas are designed for omni-directional characteristics in the horizontal plane -- dielectric rod antennas with periodic corrugations and tapered dielectric disk antennas. Another structure of interest was a low-profile microstrip patch array.

4.2 Leaky Wave Antennas

Professor Raj Mittra described extensive studies on surface wave and leaky wave antennas. Highlights of his talk and related discussion are summarized as follows:

- A good transition from a conventional waveguide to a dielectric structure is critical in the design of dielectric leaky-wave antennas. Poor designs of this transition considerably degrade inherent antenna characteristics.

- The individual grating element radiates as small an amount of energy as possible if the sharpest beam possible is desired. However, if this is attempted, the antenna becomes exceedingly long for a millimeter-wave application.

- A number of tapers have been studied for improving the performance of a leaky-wave antenna. It is important to let the electromagnetic energy radiate out within a reasonable length; otherwise, a lot of energy is left unradiated at the end of the antenna structure.

- The use of a ground plane allows radiation only in the upper hemisphere. However, a better approach is to use a long duct in which a grating antenna is placed. By designing a duct with an appropriate taper, in which the cross-section looks like a horn, we can control the radiation pattern in the sideward direction. The pattern is substantially broader than the azimuthal of the antenna.

4.3 Microstrip Patch Antennas for Millimeter-Wave Application

Dr. Donald Huebner presented a reivew of microstrip antenna development based upon current printed circuit technology.

- Microstrip antenna arrays for use at 35 GHz and 60 GHz have been developed and the technology appears suitable for antennas up to 100 GHz. Work at 35 GHz has included a 4x4 element array with a 32x32 element array. A group of four 24-element linear arrays has been mounted and tested on a cylindrical body for use as part of a 60 GHz fuse system.

- Technology is rapidly maturing towards feasible millimeter-wave monolithic GaAs phased arrays.

4.4 Surface-Wave Propagation

Professor A.A. Oliner discussed a possible leakage phenomenon in some types of dielectric waveguides. Although this topic was more in line with the Waveguide Session, it is included here because it addresses the phenomenon of leakage.

- Leakage from planar dielectric channel waveguides can occur in the form of unguided surface waves. As the wave propagates in this class of waveguides, the energy leaks in the transverse direction. Therefore, if characteristics of this leakage are known, it can be controlled, or at least the amount of leakage should be taken into account in the design. This leakage can also be deliberately used for creating special devices such as couplers.

4.5 Other Related Antenna Technology

- Dr. A.R. Sindoris described waveguide antenna activities at Harry Diamond Laboratory. They include sidewall slot traveling-wave arrays, broadwall non-resonant longitudinal slot traveling wave-arrays, continuous slot traveling wave arrays, dielectric rod antennas, and corrugated wall pyramidal horn antennas. Success of these antennas depends very critically on the machining capability. It was concluded that microwave antenna design techniques are applicable at 94 GHz and that waveguide antennas at 94 GHz can be fabricated with automated machines.

- Dr. Oren Kessler discussed his work with 94 GHz four-lobe monopulse feeds with 12 individual waveguide feed elements. He also described the usefulness of microstrip radiators fed by inverted microstrip lines.

V. FUTURE DIRECTIONS OF MILLIMETER WAVES

A round-table discussion session was organized at the end of the workshop to provide a dialogue among participants on future directions of millimeter-wave systems. Panel members included Professor A.A. Oliner of Polytechnic Institute of New York, Dr. James Mink of the U.S. Army Research Office, Dr. Barry Spielman of Naval Research Laboratory, Dr. Ben Eaves of MIT Lincoln Laboratory, Dr. Jim Wiltse of Georgia Institute of Technology, and Dr. Tim Fong of TRW. In addition, Dr. Hans Hieslmair of U.S. Army R&D Command surveyed the Army needs in the millimeter wave arena. Summary of the discussion is given as follows.

Prospects for continued progress and development in the millimeter-wave area appear good from the vantage point of today, although a number of uncertainties still hover ominously on the horizon. High power sources, such as gyrotrons which use the principles of traveling wave interaction, appear to be promising but require further development. Along that line, there is a dearth of devices, e.g., switches circulators, and couplers which are able to withstand high power levels. Materials, other than GaAs, for solid state devices with improved power efficiency in the 100 GHz frequency range and above will be needed.

At yet higher frequencies, e.g., above 150 GHz, all of the quasi-optical devices currently available are still very much in their infancy and much work remains to be done before they become practical.

Turning now to circuits and components, it appears likely that the future designs would see an increasing use of dielectric materials as opposed to metals.

Also, fully integrated and monolithic designs would utilize semiconducting materials and, since no such operating designs are currently available, it is conjectured that much future research in material development will be needed before such designs become operational. In the meantime, until monolithic designs are fully developed, the circuit designs will most likely employ hybrid integration.

Although sporadic references to research in non-reciprocal devices appear in the literature, there is still considerable room for development.

As for theoretical research, reliable analysis of discontinuities in open waveguides still remains a challenging problem. Likewise, the modeling of active circuits and associated cavity structures in open dielectric waveguides represents a formidably difficult task and must successfully tackled before systematic procedures for designing mixers and oscillators in open waveguides can be developed.

Finally, antennas compatible with dielectric waveguides -- typically surface-wave and leaky-wave types -- are much less versatile than conventional antennas. Coupling and transition from dielectric guides into conventional antennas, e.g., reflectors, also present a difficult problem. Two-dimensional arrays of leaky-wave antennas have yet to be built with as much flexibility as provided by waveguide arrays. Again, general-purpose power dividers, phase shifter, polarizers, and couplers have yet to be developed and will no doubt be investigated during the next few years.

APPENDIX

WORKSHOP ON MODERN MILLIMETER WAVE SYSTEMS

October 22-24, 1980

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